An analytical solution to the three-dimensional advection-dispersion problem was used to estimate dispersion effects from the RMEI location to the discharge point (DIRS 157520-Williams 2001, Enclosure 3, all). In these calculations, the groundwater flow velocity in the alluvium was assumed to be horizontal with a constant value of 18 meters (59 feet) per year, corresponding to a specific discharge rate of 2.7 meters (9 feet) per year and an effective porosity of 15 percent throughout the flow domain. These values were derived from the saturated zone site-scale model documented in DIRS 155950-BSC (2001, Section 12). Calculations were done under steady-state conditions, that is, for a source that has been discharging for a long time. The source was assumed to have constant concentration, be within a rectangular shape in the vertical plane, and centered at the repository location. Two source sizes were considered: a small source, 10 meters by 10 meters (33 feet by 33 feet), corresponding to an early failure scenario (localized failing waste package), and a large source, 3,000 meters (9,840 feet) horizontal by 10 meters (32.8 feet) vertical, corresponding to a long-term scenario in which all waste packages would fail.

The calculations were carried out for a range of dispersivities and for two assumed mass captures: 90 percent and 99 percent. The mass capture is a function of the amount of influence a well or field of wells would have in pulling mass from the plume. The results discussed here are restricted to the more conservative 99-percent capture assumption. Two important parameters were considered: the cross-section (perpendicular to flow) of the plume and the relative peak concentration at the center of the plume. As the plume traveled in the groundwater it would spread, so the cross-section would increase (thus reducing the average concentration) and the peak concentration would decrease. A reasonable approximation of distance effect can then be found by using either of these values. The two values will produce a slightly different result. Scaling factors using both approaches are discussed in the next section.

### I.4.5.3 Scaling Factors for Dose or Water Quality Concentrations at Longer Distances

Table I-12 lists the resulting scaling factors from the dispersion studies (DIRS 157520-Williams 2001, Enclosure 3, Table 2a). The values are for the assumption of 99-percent capture, the larger realistic dispersion factor set, and two source sizes. The large source size would be applied for nominal scenario peak dose and the small source for localized sources such as the early failures (prior to 10,000 years) due to package defects or igneous intrusion releases, or for doses from the human intrusion scenario. Two sets of scaling factors are listed for each source size: one based on peak concentration and one based on plume cross-section. To obtain a value of dose or groundwater quality concentration at 30 or 60 kilometers (18 or 37 miles), multiply the 18-kilometer (11-mile) value by the appropriate scaling factor. The scaled results reported in Chapter 5, Section 5.4.1, use the plume cross-section factors. This is considered the best choice because the effect of water usage by the communities would be to cause significant mixing, and the more characteristic parameter would be the plume average concentration.

## I.5 Waterborne Radioactive Material Impacts

The simulations in support of this analysis estimated the annual individual dose for the Proposed Action, Module 1, and Module 2 inventories. For the purposes of this EIS, DOE determined that the southern boundary of the controlled area would be at the southernmost point from the repository specified in 40 CFR Part 197 (36 degrees, 40 minutes, 13.6661 seconds north latitude). The RMEI location was then defined to be the point where the predominate groundwater flow crosses the boundary. Groundwater modeling indicated this point to be approximately 18 kilometers (11 miles) downgradient from the potential repository. This EIS refers to this location as the “RMEI location.” It corresponds to where the RMEI, a resident in an average farming community, would consume and use groundwater withdrawn from wells. In accordance with 40 CFR 197.35, the annual individual dose was calculated for the period of geologic stability (1 million years). These calculations include simulations for both the 10,000- and 1 million-year performance periods specified in 40 CFR 197.20 and 197.35.

**Table I-12.** Groundwater impact distance scale factors[a,b] for 99-percent captured mass, longitudinal dispersivity 100 meters,[c] horizontal dispersivity 10 meters, and vertical dispersivity 0.1 meters.

| Source | Scale factors | |
|---|---|---|
| | 18 kilometers[d] to 30 kilometers | 18 kilometers to 60 kilometers |
| Large source: 3,000 × 10 meters | | |
| Based on plume cross-section | 0.68 | 0.39 |
| Based on relative peak concentration | 0.74 | 0.46 |
| Small source: 10 × 10 meters | | |
| Based on plume cross-section | 0.70 | 0.48 |
| Based on relative peak concentration | 0.60 | 0.30 |

a. Derived from DIRS 157520-Williams (2001, Enclosure 3, Table 2a).
b. To convert an 18-kilometer result to a 30- or 60-kilometer result, multiply the dose or the concentration by the appropriate value in the table.
c. To convert meters to feet, multiply by 3.281.
d. To convert kilometers to miles, multiply by 0.6214.

The calculations in this EIS also show the peak dose for all scenarios. The location is also where a representative volume of groundwater would be withdrawn and where there would be a reasonable expectation that radiation would not exceed the limits of 40 CFR 197.30, Table 1. This EIS also reports groundwater protection values at that location.

The data from the multiple realizations can be summarized by showing time versus annual individual dose (dose histories) for the 5th-percentile, median, mean, and 95th-percentile of the output. In the manner described for TSPA–Site Recommendation (DIRS 153246-CRWMS M&O 2000, Section 2.2.4.6, pp. 2-39 to 2-40), these statistical measures were calculated for all 300 realizations of the probabilistic simulations at each time step of the annual individual dose histories. The plot of the mean represents the average of all 300 data points at each time step. For each point on the plot of the median dose, 50 percent of the data have a value greater than the plotted point and 50 percent have a value less than the plotted point. Similarly, for the 5th- and 95th-percentiles, the plotted data points are such that 95 percent of data are greater than the plotted point and 5 percent of the data points are greater than the plotted points, respectively, for each time step. The statistical measures were superimposed on plots that show all 300 realizations (often referred to as “horsetail plots”).

### I.5.1 WASTE PACKAGE FAILURE

Figure I-8 shows the waste package failure curves for the Proposed Action for the 1-million-year performance period for the higher-temperature operating mode. The figure indicates that the first waste package failures would occur within 10,000 years of repository closure. These early waste package failures result from the assumption of improper heat treatment (see Section I.2.4 and Table I-3). The 300 realizations are shown in Figure I-8. During the first 10,000 years there are some realizations showing a failure fraction of 0.00025, which when multiplied times the total waste packages (11,770) gives a maximum of 3 early waste package failures. There are some realizations that show zero failures, but this is not readily evident from the figure. Waste package failure would be the first step in releasing radionuclides for groundwater flow and transport.

Figure I-9 shows cladding perforated during the postclosure period. The calculations included the averaged impact of seismic events. The cladding failure results shown in Figure I-9 are essentially the same as those developed in the *FY01 Supplemental Science and Performance Analyses* (DIRS 154659-BSC 2001, pp. 9-19 to 9-23).

## I.5.2 ANNUAL INDIVIDUAL DOSE FOR 10,000 YEARS AFTER CLOSURE

This section presents graphic representations of annual individual doses for the inventories described in Section I.3 and the scenarios described in Section I.4. The performance period for the calculations in this EIS was generally 1 million years after repository closure except in the case of the igneous activity scenarios. The annual dose histories for the igneous activity scenarios were only calculated for 100,000 years after closure because the releases from the nominal scenario dominate after that time. In addition to the graphic presentations, Table I-13 lists the values of the peak mean annual individual dose for all scenarios that would occur in the 10,000-, 100,000-, and 1-million-year postclosure performance periods, in accordance with 40 CFR 197.20, 197.25, and 197.35. Table I-14 lists the same information for the peak 95th-percentile annual individual dose.

**Table I-13.** Peak mean annual individual doses (millirem) for analyzed inventories, scenarios, and temperature operating modes.[a,b]

| Modeled inventory, scenario, and operating mode | 10,000 years | | 100,000 years | | 1 million years | |
|---|---|---|---|---|---|---|
| | Value | Year | Value | Year | Value | Year |
| Proposed Action, nominal, higher-temperature | 0.000017 | 4,875 | 0.12 | 99,500 | 152.5 | 476,000 |
| Proposed Action, nominal lower-temperature | 0.000011 | 3,437.5 | 0.085 | 99,500 | 122.2 | 476,000 |
| Inventory Module 1, nominal, higher-temperature | 0.000027 | 4,937.5 | 0.16 | 100,000 | 237.9 | 476,000 |
| Inventory Module 2, nominal, higher-temperature[c] | 0.00066 | 2,875 | 0.00066 | 2,875 | 0.33 | 208,000 |
| Proposed Action, igneous activity, higher-temperature | 0.10 | 312.5 | 0.10 | 312.5 | NC[d] | NC |
| Proposed Action, igneous activity, lower-temperature | 0.10 | 312.5 | 0.10 | 312.5 | NC | NC |
| Proposed Action, igneous activity (intrusive only), higher-temperature | 0.00043 | 10,000 | 0.021 | 48,000 | NC | NC |
| Proposed Action, igneous activity (intrusive only), lower-temperature | 0.00050 | 10,000 | 0.028 | 48,000 | NC | NC |
| Proposed Action, igneous activity (eruptive only), higher-temperature | 0.10 | 312.5 | 0.10 | 312.5 | NC | NC |
| Proposed Action, igneous activity (eruptive only), lower-temperature | 0.10 | 312.5 | 0.10 | 312.5 | NC | NC |
| Proposed Action, human intrusion at 30,000 years, higher-temperature | NA[e] | NA | 0.0017 | 30,562.5 | 0.0023 | 108,000 |

a. Adapted from DIRS 157307-BSC (2001, Enclosure 1).
b. These data are based on the same probabilistic annual water usage model used in the TSPA–Site Recommendation (not 3,000 acre-feet per year).
c. Module 2 runs only included the incremental effect of the additional inventory from Greater-Than-Class-C and Special-Performance-Assessment-Required waste.
d. NC = not calculated.
e. NA = not applicable.

## I.5.3 ANNUAL INDIVIDUAL DOSE FOR 1,000,000 YEARS AFTER CLOSURE

Results for annual individual dose calculations for 1 million years following closure are discussed for the Proposed Action (Section I.5.3.1), Inventory Module 1 (Section I.5.3.2) and Inventory Module 2 (Section I.5.3.3).

**Table I-14.** Peak 95th-percentile annual individual doses (millirem) for analyzed inventories, scenarios, and temperature operating modes.[a,b]

| Modeled inventory, scenario, and operating mode | 10,000 years | | 100,000 years | | 1,000,000 years | |
|---|---|---|---|---|---|---|
| | Value | Year | Value | Year | Value | Year |
| Proposed Action, nominal, higher-temperature | 0.00012 | 4,937.5 | 0.040 | 99,500 | 618.0 | 408,000 |
| Proposed Action, nominal, lower-temperature | 0.000086 | 5,000 | 0.034 | 100,000 | 513.2 | 408,000 |
| Inventory Module 1, nominal, higher-temperature | 0.00018 | 4,125 | 0.079 | 100,000 | 976.7 | 476,000 |
| Inventory Module 2, nominal, higher-temperature[c] | 0[d] | NA[e] | 0.0013 | 100,000 | 1.5 | 208,000 |
| Proposed Action, igneous activity, higher-temperature | 0.41 | 312.5 | 0.41 | 312.5 | NC[f] | NC |
| Proposed Action, igneous activity, lower-temperature | 0.41 | 312.5 | 0.41 | 312.5 | NC | NC |
| Proposed Action, igneous activity (intrusive only), higher-temperature | 0.00029 | 9,750 | 0.052 | 100,000 | NC | NC |
| Proposed Action, igneous activity (intrusive only), lower-temperature | 0.00031 | 9,875 | 0.033 | 48,000 | NC | NC |
| Proposed Action, igneous activity (eruptive only), higher-temperature | 0.41 | 312.5 | 0.41 | 312.5 | NC | NC |
| Proposed Action, igneous activity (eruptive only), lower-temperature | 0.41 | 312.5 | 0.41 | 312.5 | NC | NC |
| Proposed Action, human intrusion at 30,000 years, higher-temperature | NA | NA | 0.0045 | 38,500 | 0.0045 | 38,400 |

a. Adapted from DIRS 157307-BSC 2001, Enclosure 1.
b. These data are based on the same probabilistic annual water usage model used in the TSPA–Site Recommendation (not 3,000 acre-feet per year).
c. Module 2 runs only included the incremental effect of the additional inventory from Greater-Than-Class-C and Special-Performance-Assessment-Required waste.
d. The mean dose is driven by 3 realizations that experience early failures; no other realizations result in a dose before 10,000 years so that the 95th-percentile value is zero.
e. NA = not applicable.
f. NC = not calculated.

### I.5.3.1 Annual Individual Dose for the Proposed Action Inventory, Higher- and Lower-Temperature Repository Operating Modes

Figure I-10 shows the mean annual individual dose results of the 300 probabilistic simulations for the higher-temperature repository operating mode (approximately 56 MTHM per acre) for the Proposed Action inventory at the RMEI location for 1 million years after repository closure. Figure I-11 shows the relative contribution of selected radionuclides that contribute most to the total mean annual dose due to all radionuclides. Figure I-12 shows the results of the 300 probabilistic simulations of the Proposed Action inventory, higher-temperature operating mode, at the RMEI location for 1 million years after repository closure. This figure shows the results for each realization and the 5th-percentile, mean, median, and 95th-percentile of these simulations.

Figure I-10 also shows representations of the mean annual individual dose results of the 300 probabilistic simulations for the lower-temperature operating mode (approximately 45 MTHM per acre) for the Proposed Action inventory at the RMEI location for 1 million years after repository closure. Because Figure I-10 shows little difference between the annual individual dose histories calculated for the higher-temperature and the lower-temperature operating modes, the remaining scenarios, other than the igneous activity scenario, were simulated only for the higher-temperature operating mode. Figure I-13 shows the results of the 300 probabilistic simulations of the Proposed Action inventory, lower-temperature operating mode, at the RMEI location for 1 million years after repository closure. This figure shows the results for each realization and the 5th-percentile, mean, median, and 95th-percentile of these simulations.

### I.5.3.2 Annual Individual Dose for Inventory Module 1, Higher-Temperature Repository Operating Mode

Figure I-14 displays the annual dose histories for the 300 probabilistic simulations of the expanded-inventory Module 1, higher-temperature operating mode at the RMEI location for 1 million years after repository closure. This figure shows the results for each realization and the 5th-percentile, mean, median, and 95th-percentile of these simulations.

### I.5.3.3 Annual Individual Dose for Inventory Module 2, Higher-Temperature Repository Operating Mode

A GoldSim simulation was performed for a case that included only the Greater-Than-Class-C and Special-Performance-Assessment-Required components of the Module 2 inventory. The case did not include the other components of the Module 2 inventory (that is, the Module 1 inventory). The GoldSim simulation for only the Module 2 Greater-Than-Class-C and Special-Performance-Assessment-Required inventory, higher-temperature operating mode, was performed as a separate probabilistic case at the RMEI location. Figure I-15 shows the results of this simulation as the mean annual individual dose due to the radioactive components of this material. The effects of nonradioactive components of this waste are not included in the analysis.

Figure I-16 is a comparison plot of the mean annual dose versus time for the Proposed Action, Module 1, and the Greater-Than-Class-C and Special-Performance-Assessment-Required waste portion of the Module 2 inventories at the higher-temperature operating mode at the RMEI location. These results show that during the first 10,000 years, the mean annual individual dose due to the Greater-Than-Class-C and Special-Performance-Assessment-Required components of the Module 2 inventory would be greater than that calculated for the Proposed Action and Module 1 inventories, but still essentially zero. After 10,000 years, the dose due to the Greater-Than-Class-C and Special-Performance-Assessment-Required components of the Module 2 inventory would be about two orders of magnitude less than that calculated for the Proposed Action and Module 1 inventories. These results indicate that the addition of the Greater-Than-Class-C and Special-Performance-Assessment-Required waste to the Module 1 inventory would not materially increase the mean annual individual dose. Based on this comparison, separate probabilistic simulations were not run for the entire Inventory Module 2.

### I.5.3.4 Annual Individual Dose for Igneous Activity Scenario, Higher- and Lower-Temperature Repository Operating Modes

The performance of a Yucca Mountain repository was evaluated for a combined igneous activity scenario that included both an igneous event and a volcanic eruption. The combined scenario was simulated for the higher- and lower-temperature repository operating modes for the Proposed Action inventory. Annual dose histories were not calculated for the igneous activity scenario for Modules 1 and 2.

Figure I-17 shows representations of the probability-weighted annual individual dose histories for 500 of the 5,000 probabilistic simulations for the igneous activity scenario, higher-temperature repository operating mode (approximately 56 MTHM per acre) for the Proposed Action inventory at the RMEI location for 100,000 years after repository closure. Figure I-17 also shows the 5th-percentile, mean, median, and 95th-percentile of all 5,000 igneous activity simulations. The results shown in the figure represent the combined effect of both the igneous-intrusion and eruptive events.

Figure I-18 shows the mean annual individual dose versus time for the igneous activity scenario for the Proposed Action inventory for the higher-temperature operating mode at the RMEI location. The figure also shows the mean results for both the eruptive and intrusive events. Figure I-19 shows the mean annual individual dose for the igneous activity scenarios, representing the sum of the igneous and eruptive events, Proposed Action inventory for the higher- and lower-temperature operating modes at the RMEI location.

Figure I-20 shows representations of the probability-weighted annual individual dose histories for 500 of the 5,000 probabilistic simulations for the igneous activity scenario, lower-temperature repository operating mode (approximately 45 MTHM per acre) for the Proposed Action inventory at the RMEI location for 100,000 years after repository closure. Figure I-20 also shows the 5th-percentile, mean, median, and 95th-percentile of all 5,000 igneous activity simulations. The results presented in this figure represent the combined effect of both the igneous intrusion and eruptive events.

Figure I-21 shows the mean individual annual dose versus time for the igneous activity scenario for the Proposed Action inventory for the lower-temperature repository operating mode at the RMEI location. The figure also displays the mean results for both the eruptive and intrusive events.

#### I.5.3.5 Annual Individual Dose for the Human Intrusion Scenario

Figure I-22 displays representations of the annual individual dose results of the 300 probabilistic simulations for the human intrusion scenario, 30,000 years after repository closure, Proposed Action inventory for the higher-temperature operating mode at the RMEI location. Figure I-22 displays the results for each simulation and the 5th-percentile, median, mean, and 95th-percentile of these simulations.

### I.5.4 COMPARISON TO GROUNDWATER PROTECTION STANDARDS

An analysis for groundwater protection was conducted in accordance with the Environmental Protection Agency Final Rule 40 CFR 197.30 and 197.31). The rule is based on meeting three groundwater radionuclide-concentration levels. The first is the maximum annual concentration of radium-226 and -228 in a representative volume of 3.7 million cubic meters (3,000 acre-feet) of groundwater in a release from the proposed repository. The second groundwater concentration is for the gross alpha activity (excluding radon and uranium) in the representative volume of groundwater. Both calculations apply to releases from both natural sources and releases from the repository at the same location as the RMEI. The third groundwater-protection calculation is the dose to the whole body or any organ of a human for beta- and photon-emitting radionuclides released from the repository. The human would consume 2.0 liters (0.53 gallon) per day from the representative volume of groundwater. This groundwater would be withdrawn annually from an aquifer containing less than 10,000 milligrams per liter (1.34 ounces per gallon) of total dissolved solids, and centered on the highest concentration in the plume of contamination at the same location as the RMEI. The results of the calculations for this EIS produced data consistent with the Environmental Protection Agency Final Rule and are presented graphically and in tabular form.

Figure I-23 shows the mean activity concentrations of gross alpha activity and total radium (radium-226 plus radium-228) in the representative volume of groundwater for the Proposed Action inventory, higher-temperature repository operating mode. The concentrations are calculated for a representative volume of water of 3.7 million cubic meters (exactly 3,000 acre-feet per year) at the same location as the RMEI at the accessible environment as described in 40 CFR 197.30. Naturally occurring background radionuclide concentrations were not included because the calculated values are negligible compared to background concentrations up to 100,000 years after closure. Figure I-24 shows the same information for the lower-temperature operating mode.

Figure I-25 shows the mean dose to the whole body or any organ for technetium-99, carbon-14, and iodine-129, the prominent beta and photon-emitting radionuclides (DIRS 154659-BSC 2001, Volume 2, Section 4.1.4, pp. 4 to 11) for the Proposed Action inventory, higher-temperature repository operating mode, for the 1-million-year performance period. Figure I-26 shows the same information for the lower-temperature operating mode.

The data developed for the groundwater protection standard are summarized in Table I-15, which lists the peak mean gross alpha activity by scenario for various performance periods; Table I-16, which lists peak total radium concentration by scenario for various performance periods; and Table I-17, which lists the combined whole-body or organ doses in 10,000 years for the total of all beta- and photon-emitting radionuclides. The mean whole-body or organ dose was calculated by diluting the model-predicted annual activity releases of iodine-129, carbon-14, and technetium-99 [the prominent beta and photon-emitting radionuclides (DIRS 154659-BSC 2001, Volume 2, Section 4.1.4, pp. 4 to 11)] in the representative volume of groundwater (3,000 acre-feet per year). The resulting concentrations for each time step were converted to equivalent doses by scaling the appropriate dose conversion factor (4 millirem per 2,000 picocurie per liter for carbon-14; 4 millirem per 1 picocurie per liter for iodine-129; and 4 millirem per 900 picocurie for technetium 99). Calculating the sum of these three radionuclide doses for each time step produced a time history of whole-body or organ dose; the peak within 10,000 years was identified and is reported in Table I-17. This process is repeated for 95th-percentile whole-body or organ dose using model-predicted 95th-percentile annual activity releases of the prominent beta and photon-emitting radionuclides.

# I.6 Waterborne Chemically Toxic Material Impacts

Several materials that are chemically toxic would be used in the construction of the repository. A screening analysis was used to determine which, if any, of these materials would have the potential to be transported to the accessible environment in quantities sufficient to be toxic to humans.

Chemicals included in the substance list for the Environmental Protection Agency's Integrated Risk Information System (DIRS 103705-EPA 1997, all; DIRS 148219, 148221, 148224, 148227, 148228, 148229, and 148233-EPA 1999, all) were evaluated to determine a concentration that would be found in drinking water in a well downgradient from the repository. The chemicals on the Integrated Risk Information System substance list that would be in the repository are barium, boron, cadmium, chromium, copper, lead, manganese, mercury, molybdenum, nickel, selenium, uranium, vanadium, and zinc.

## I.6.1 SCREENING ANALYSIS

The results of the analysis of long-term performance for radionuclides detailed in Section I.5 show that, at most, three waste packages would be breached prior to 10,000 years (due to improper heat treatment) under the Proposed Action. The period of consideration for chemical toxic materials impacts was 10,000 years. Therefore, only toxic materials outside the waste package were judged to be of concern in this analysis. These are chromium, copper, manganese, molybdenum, nickel, and vanadium.

### I.6.1.1 Maximum Source Concentrations of Chemically Toxic Materials in the Repository

Maximum source concentrations were calculated to provide the maximum possible concentration of that element in water entering the unsaturated zone. For materials that were not principally part of the Alloy-22 (copper and manganese), the maximum source concentration was taken to be the solubility of the material in repository water. The solubilities were obtained by modeling with the EQ3 computer code (DIRS 100836-Wolery 1992, all). The simulations were started with water from well J-13 near the Yucca Mountain site (DIRS 100814-Harrar et al. 1990, all). EQ3 calculates chemical equilibrium of a system so that, by making successive runs with gradually increasing aqueous concentrations of an element,